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A CONCEPT FOR UNDERGROUND SITING OF NUCLEAR POWER REACTORS

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May 1973

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Contents

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Abstract

Preliminary design criteria developed for a general case show that underground siting of nuclear power reactors is practicable and safe. The concept calls for open-pit excavation to allow construction of the reactor containment structure in nearly any geological medium, although some attention must be given to local ground-water conditions. The required depth of excavation for the structure housing the nuclear system and steam generators is about 300 ft. After being constructed in the pit, this structure is covered with selected backfill material. The backfill is chosen for its well-defined low permeability so that it will confine within a small envelope any radioactivity release that might result from a rupture of the containment structure. The additional cost of putting the nuclear portion of the system underground is only a small fraction of the cost of a conventional all-surface nuclear power plant. The turbine/generator sets should be located at or near the surface for minimum capital expenditure and operating cost. Underground reactor siting as proposed herein will apparently require no new technology. An extensive body of relevant experience provides confidence that radioactive material can be confined under the conditions of a reactor accident.

Introduction

Until recent years, central-station power plants have customarily been located at surface sites close to a fuel source, the power users, and a heat sink. Little if any serious consideration was given to sites other than on surface land. The advent of nuclear power reactors has added a new dimension to the siting question; although the location of the fuel source is no longer significant, the hazard posed by an accidental radiation release is.

The historic, and certainly reasonable, approach to providing safe central-station nuclear power plants has been to improve engineered safeguards against the release of radiation to the population from surface-sited reactors. In particular, significant advancements have been made in the design and construction of containment vessels. However, there still exist doubts that present surface-sited containment systems will adequately protect the public from release of radiation to the environment in the event of a catastrophic reactor accident. Underground and underwater siting have been suggested as means of providing increased containment protection; this study deals with underground siting.

Locating power reactors underground offers other advantages besides safety: It is attractive from an esthetic standpoint, it provides greater biological shielding, it would permit urban or near-urban siting with resulting savings in power transmission, and it would free surface sites for other purposes. Although any or all of these may prove to be key advantages, this study focuses on underground siting as a means of eliminating the release of radioactivity to the environment as a result of a reactor accident, an earthquake, a tornado, or some other unusual occurrence.

A number of studies have been made[1-5] of underground siting of nuclear power reactors; they were predicated on placing all of the components in caverns constructed in solid rock masses. The present model proposes that only the nuclear heat source and the primary steam generator be located underground and that the turbines and other power conversion equipment be located at or very near ground level. Furthermore, it is suggested that massive rock formations are not required; rather, total containment can best be obtained in many geologic formations by constructing the reactor and steam generator in an open pit several hundred feet deep[6] and backfilling it with a material having a known and controllable permeability. The reactor containment structure could then be built by normal construction techniques. Experience with engineered backfill shows that such an approach would be feasible. Calculations indicate

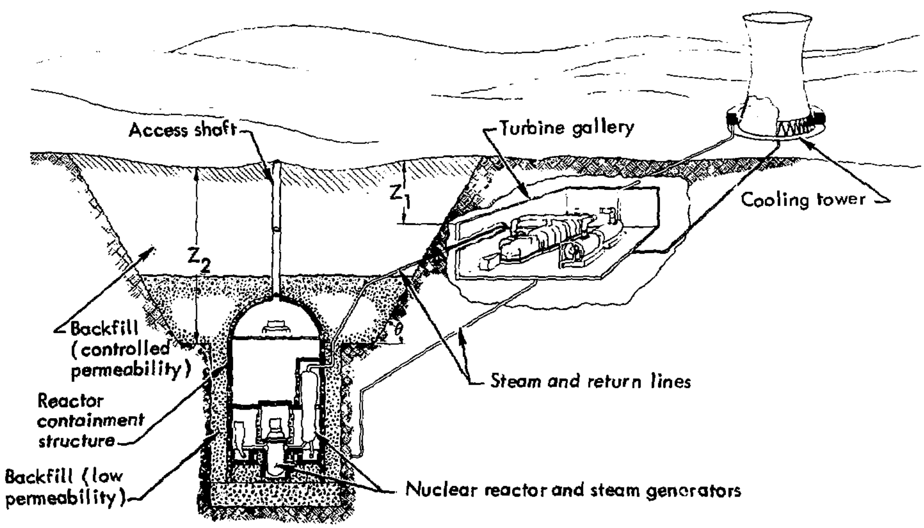

Fig. 1. Concept for underground siting of nuclear power reactors. The parameters Z_1, Z_2, θ, and soil type were varied in the study.

not only that such an approach is feasible, but that it appears to introduce little additional cost while accomplishing the objective of radioactivity confinement most effectively. This technique appears to be suitable for all reactor types: water cooled, gas cooled, or fast breeder. Figure 1 shows a typical underground installation.

Preliminary results of this study show that nuclear reactors for large central-station power plants can be sited underground in a practicable and economic manner that results in enhanced safety. The overall cost penalties associated with excavation and a structurally appropriate reactor containment structure appear to be considerably less than 5% of the cost of an equivalent surface-sited 1100-MWe plant.

Features of the Underground System

To capitalize on available technical information and to permit realistic comparison with existing power plants, this study is based on a 1100-MWe power plant. The study applies to any type of reactor, with the condition that reactor energy be transported to conventional turbine generators in light-water steam generated in the reactor containment structure.

ACCIDENT MODEL AND ITS RELATION TO TEST-SITE EXPERIENCE

The containment requirements considered in this study were based on conventional practice in nuclear-plant design.[7] The peak design pressure in the nuclear system containment structure was taken to be 70 psia. This peak pressure assumes the conditions of the maximum credible accident, including double-ended shear in the steam supply system piping. It further assumes that a loss-of-coolant accident (LOCA) is properly responded to by the emergency core-cooling system (ECCS) and a modest pressure-suppression system, so that the final pressure within the structure is compatible with the normal design pressure of 15 to 60 psig.[7] The burial depth of the containment structure was set at the depth required to provide a nominal 70-psia static overburden pressure to balance the internal design pressure.

Containing the radioactive products resulting from an underground reactor malfunction is different from containing the products of an underground nuclear explosion. The primary differences lie in the partitioning of energy and in the time scales of the two phenomena. In the case of the nuclear explosive, all of the yield is produced within a few hundreths of a microsecond, and the resulting radiant energy immediately melts and vaporizes a volume of material on the order of 70 tons per kiloton of energy yield.[8] (One kiloton of high-explosive energy equals 10^{12} cal; in this context, it is difficult to postulate a reactor accident having an equivalent primary energy release greater than 10^{10} cal.) In the case of a nuclear reactor accident, the majority of the energy release is produced within the solid, clad fuel elements over a period of many microseconds.

Then several milliseconds pass while the fuel becomes partially molten, the cladding ruptures, and the fuel and coolant react. Although a large volume of steam may be produced, the pressure rise occurs so slowly that many more milliseconds must pass before the primary pressure vessel can be ruptured. Only then can the escaping high-pressure condensable vapor provide a shock to the containment structure. The total available energy at this time is not expected to be significantly more than a few percent of the original energy released in the fuel. The major part of the energy produced is used up in melting the core and rupturing the reactor pressure vessel. There is then insufficient energy to impart more than a strong gas shock to the structure walls. A significant benefit arises from burial of the containment structure; because of the inertia of the backfill material, the shock stress required for rupture effectively doubles for buried vessels as compared to bare structures.

Detailed assessment of the progress of a reactor accident from inception through dynamic response of the pressure vessel, containment structure, and surrounding soil is required to assess the structure response properly. In particular, this calculation[9] would include the effectiveness of the concrete outer shell and backfill materials in ameliorating the shock loading. Calculations of this kind are standard in our normal nuclear testing,[10,11] but they require considerable effort and were not performed as part of this study.

Experience with nuclear detonations shows that closure systems for all required penetrations of the reactor structure are entirely practicable. For underground nuclear experiments, reliable pipe-closure systems have been developed that are capable of closing in less than a millisecond while withstanding hundreds of g's and thousands of psi loading. Longer pipe under the above concept will allow for redundant and independently actuated closure systems.

CONTAINMENT-STRUCTURE DESIGN SUMMARY

A preliminary static structural design analysis was conducted to obtain sizing criteria of the reactor containment structure shown in Fig. 2, with particular reference to the strength and stability of a large, composite-wall containment structure.[12,13] The findings include a comparison of the excavation concept with construction of a large cavity in solid rock.[14] Table 1 gives dimensions of the steel/concrete composite wall structure for the wet soil condition derived from a static, elastic analysis. A dynamic evaluation of the strength of the containment structure and the permeability characteristics of the backfill material was then performed on the basis of the geometry and dimensions derived from the static study.

The particular features of the containment-structure design are:

- Sufficient diameter and height to receive existing PWR and BWR systems and planned HTGR or LMFBR systems complete with handling crane and fuel storage area.
- A 10-ft-diam access tube for men and equipment. Since the reactor is placed in the containment structure during construction, a large access

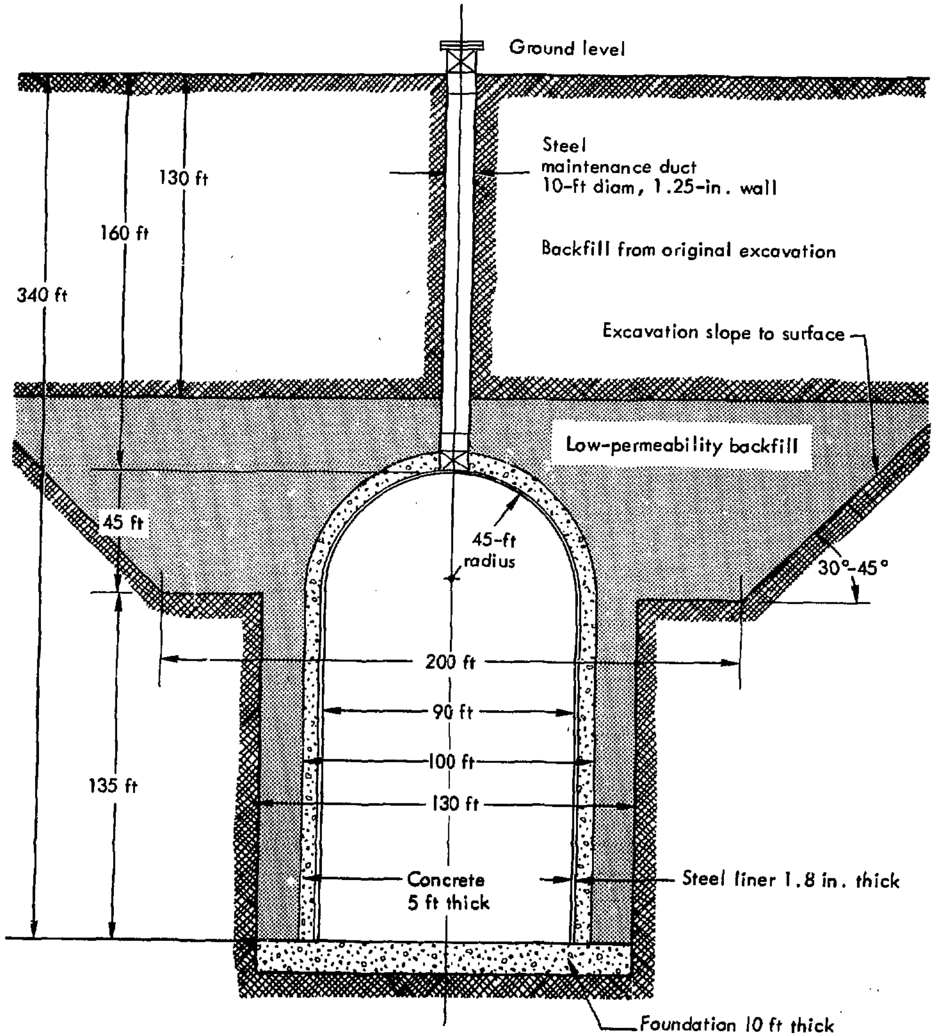

Fig. 2. Reactor containment structure and excavation envelope (no scale).

is not needed. In the case of PWR or BWR systems this tube can provide a significant ECCS backup if it is water filled.

- Foundation independence from bedrock requirement.

The containment structure, excavation, and backfill are shown in Fig. 2. The maximum depth of the excavation is based on the proportions of the containment structure and the minimum overburden pressure required at the junction of the

Table 1. Criteria for the wall thickness of the reactor containment structure.

Case	Thickness of steel liner (in.)	Thickness of concrete shell (in.)
Surface, conventional	0.75	24
Underground, dry soil	1.0	24
Underground, wet soil	1.8	60

access tube and the domed structure.[15] This pressure determines the minimum depth of the containment structure and therefore the minimum length of the access tube for the preliminary criterion that overburden pressure be equal to the design equilibrium internal pressure in the containment structure in the event of a nuclear accident.

The thickness of the steel liner of the containment structure is an important variable from the point of view of manufacturing and cost. The required thickness is based on the selected pressure criterion and the interaction between the steel liner, the concrete shell, and the surrounding soil. The most reasonable approach is to assume a static head of water acting on the reactor containment structure (the wet soil condition).[12]

The usable volume of the containment structure within the cylindrical and domed portions is assumed to be 10^6 ft^3, and the ratio of cylinder height to inner radius is taken to be 3. The volume and aspect ratio chosen represent the typical structure found in the literature.

The estimated difference in cost between the proposed underground structure in wet soil and a conventional surface structure is only 0.75%. This low cost penalty is based on $1/lb for steel liner in place and $80/$yd^3$ for concrete in place. The same construction methods would apply on the surface or at the bottom of the excavated pit.

THERMAL AND PUMPING CONSIDERATIONS

An apparent source of difficulty with an underground reactor is the performance penalty associated with thermal and head losses in the working-fluid or condenser-fluid lines. This possibility was examined parametrically to arrive at appropriate locations for the reactor, turbine, and cooling tower. The general conclusion supported by the analysis places the turbine at or near the surface. Tables 2 and 3 give thermophysical and pipe-size data used in the analysis.

The thermodynamic system analyzed consisted of steam, feedwater return, and condenser water lines. The sizes of the steam and feedwater lines chosen conformed to an existing plant of the same capacity. The number and size of the condenser water lines were chosen to keep the fluid velocity in the range of common commercial practice. To simplify the analysis, it was also assumed that:

1. Pressure drops in the feedwater and condenser line are due only to pipe friction.
2. Fluid properties are constant.
3. Plant thermal efficiency is 33%.
4. Pump efficiency is 85%.
5. Plant electrical cost is $0.006/kWh.
6. Inside convection resistance and pipe thermal capacity are negligible.

Table 2. Thermophysical data used in thermal and head-loss analysis.

	Pressure (psia)	Temperature (°F)	Density (lb/ft^3)	Viscosity (lb/hr-ft)	Flow rate (lb/hr)	Thermal conductivity (Btu/hr-ft-°F)	Specific heat (Btu/lb-°F)
Steam	1100	556	2.499	0.072	1.4×10^6		
Feedwater	1100	430	52.37	0.314	1.4×10^6		
Condenser	~50-100	90	62.11	1.85	7.51×10^8 (10° ΔT) 5.01×10^8 (15° ΔT) 3.75×10^8 (20° ΔT)		
Earth			160			1.5	0.20
Insulation			12.5			0.023	0.16

Table 3. Pipe size.

Piping size	Number	Inside diameter (in.)	Length (ft)
Steam line	2	44	340-460
Feedwater line	1	30	340-460
Condenser lines	8	66	50-460

7. The base ground temperature is 70°F.
8. Piping insulation is equivalent to 6 in. of glass wool.

Figure 3 shows additional feed-water and condenser-water pumping power in terms of plant gross electrical output and additional annual operating cost as functions of reactor depth, excavation slope, and relative position of the turbine and reactor. Note that placement of the turbines and their peripheral equipment at the reactor level may result in unreasonable operating costs. For example, for a reactor burial depth of 400 ft, an excavation slope of 30°, and a condenser water-temperature difference of 10°F, the annual plant pumping cost is $3,800,000 more than for a conventional existing plant of the same capacity. If the turbines are located on the surface, the differential cost drops to about $4,400 per year.

The pressure drop in the steam line is less than 1% of the initial pressure and should present no difficulty in the operation of the plant.

Heat will be lost to the environment from the steam and feedwater return lines. The extent of these losses depends on the design of the line emplacement and on the thermal properties of their environment. The magnitude of these losses and the resulting temperature rise of the environment was determined by treating the question as a one-dimensional radial heat-conduction problem.

Figures 4 and 5 show the radial temperature distribution and heat loss per unit length of pipe for both uninsulated and modestly insulated lines. Figure 6 shows the heat loss in terms of gross plant electric output. In the worst case, i.e., the longest pipe lengths, the heat loss is less than 0.04% of the gross electrical output of the plant after only 1 hr of operation for the insulated case.

On the basis of these calculations, the following conclusions are drawn:

- The turbine generators, condensers, preheaters, and feed pumps should

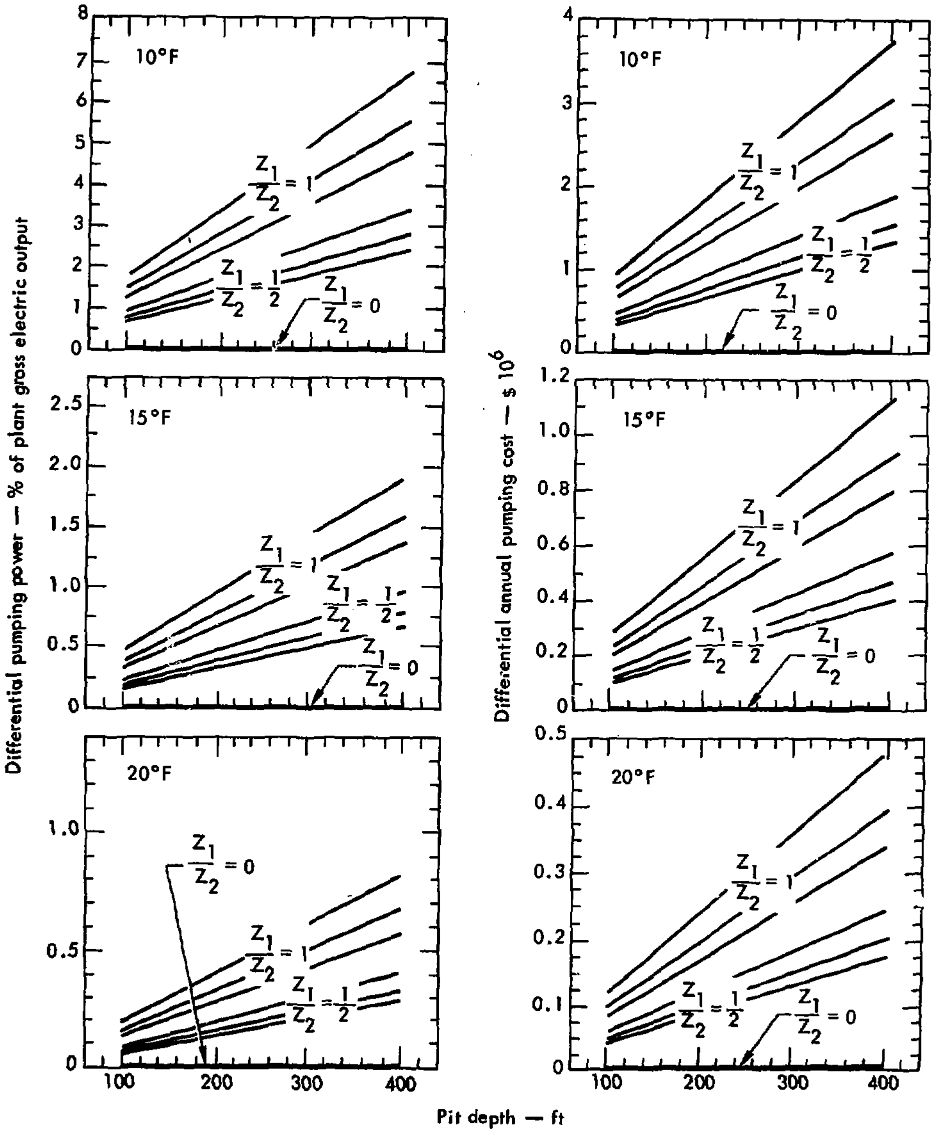

Fig. 3. Differential pumping power and annual costs versus depth of reactor containment structure and turbine gallery. Data are given for three condenser water temperature differences: 10°F, 15°F, and 20°F, as indicated. Z_1 and Z_2 are the burial depths of the turbine and the reactor, respectively (see Fig. 1). For Z_1/Z_2 ratios of 1 and 1/2, three curves are shown; from top to bottom in each group they are for excavation slopes of 30°, 37.5°, and 45°, respectively.

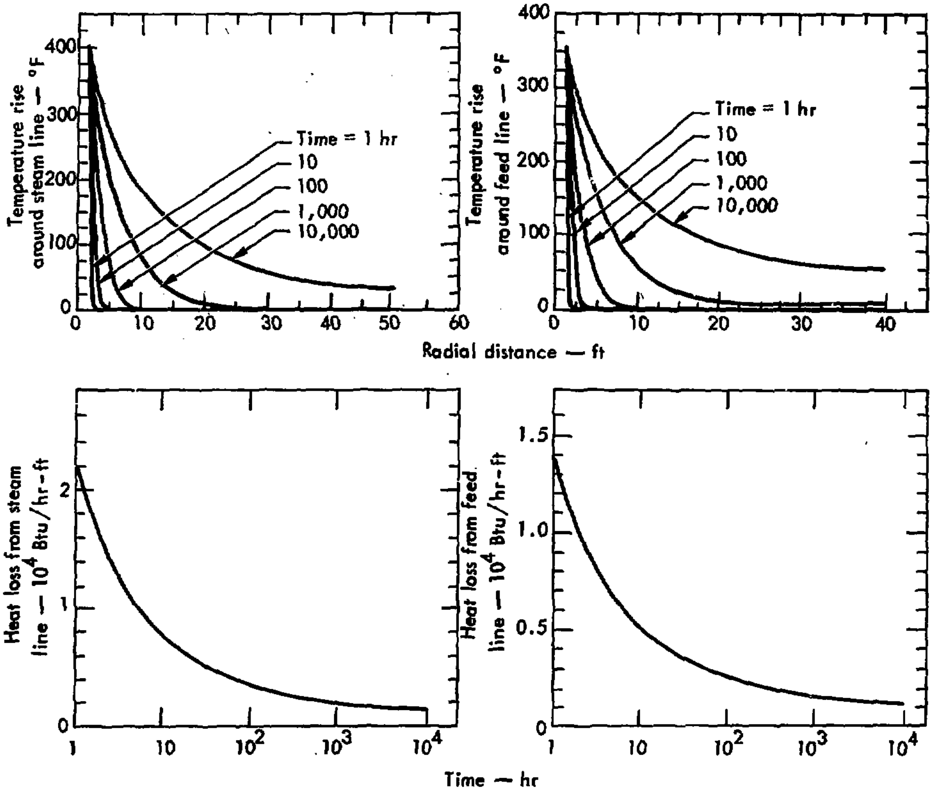

Fig. 4. Ground-temperature rise and pipe heat loss for uninsulated steam and feed lines.

be located at or near the surface.

- Heat losses from the steam and feedwater lines can be sustained even during start-up from a modestly insulated system.
- No new technology appears to be involved in the placement of piping or provision for insulation.
- The resultant rise of environmental temperature during the lifetime of operation should not present any significant problems.
- The plant performance penalty appears to be negligible.

ROCK CAVITY VERSUS EXCAVATION

The design for large openings in rock (having a span of 50 ft or more) is normally based on static, elastic analysis involving gravity loads and test data on elastic displacements during excavation.[14,16] The pressure acting on the roof of the cavity is normally assumed to be equal to the product of the density and the height of loose rock less its cohesion strength. The extent of loose rock in the cavity walls is on the order of 5 to 10% of the cavity height. In a relatively large cavity in rock, numerous rock bolts must be used to support the loose material. These bolts are usually pretensioned to about two-thirds of the yield strength of the bolt material. Bolt length depends on the size of the yield zone in the rock, which in practice works out to be about one-fourth to one-third of the cavity span. The variation of material properties and the presence of complex boundary conditions in the elastic-plastic region near the cavity boundary make the theoretical analysis for rock-bolt design difficult. One of the primary functions of the rock bolts is to apply sufficient pressure to the rock surface to restrain the supported rock mass and to prevent large displacements. Furthermore, rock bolts must be long enough to penetrate the loose

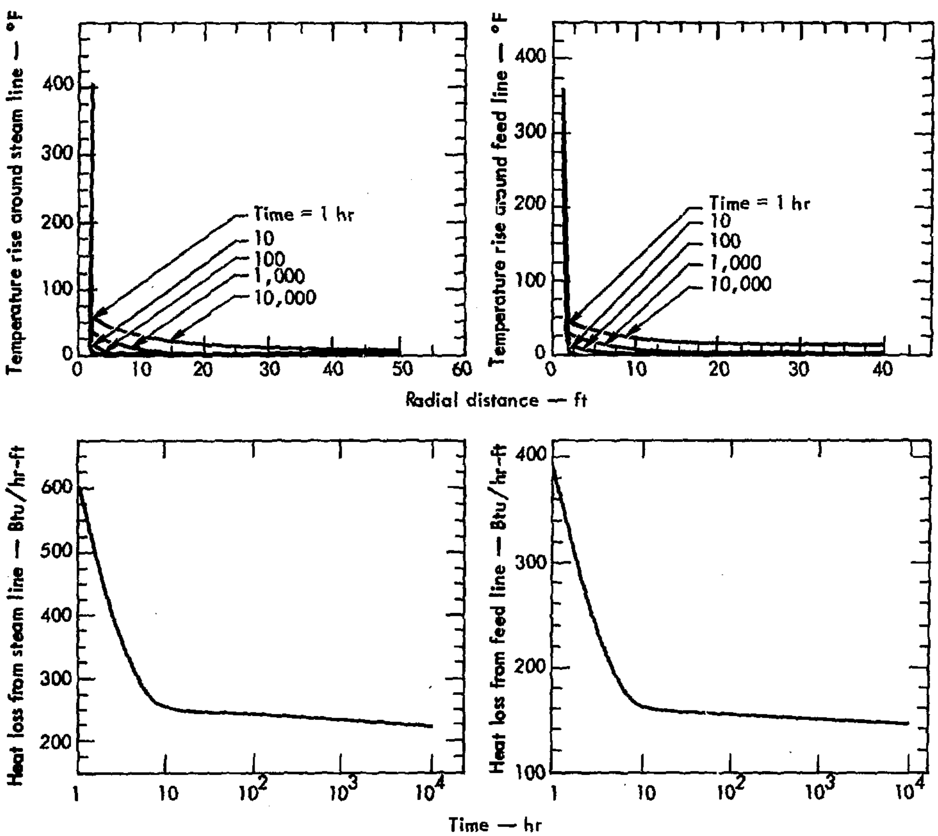

Fig. 5. Ground-temperature rise and pipe heat loss for insulated steam and feed lines.

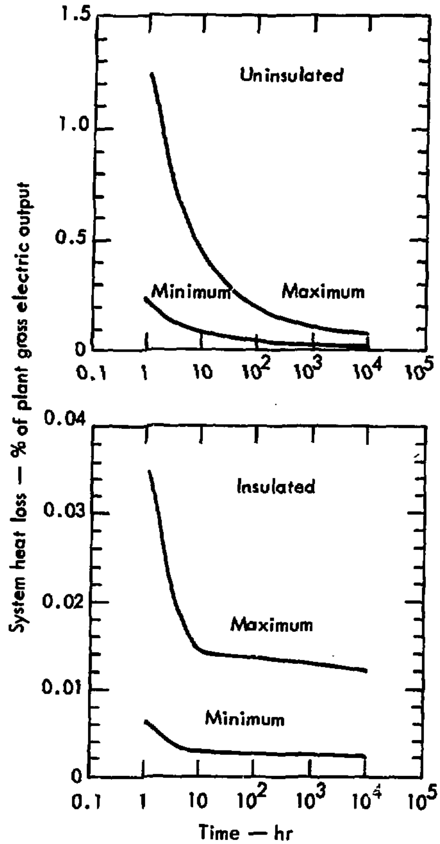

Fig. 6. Line heat loss in terms of plant output for insulated and uninsulated lines. "Maximum" and "minimum" refer to the longest and shortest lines considered (see Table 3).

and plastically deformed region, and they must be sufficiently close together to prevent rock failure between the bolts. Since rock deformation is a factor controlling the strength of the supported rock mass, one of the major variables is the amount of support pressure that can be allowed on a particular rock surface.

These theoretical and practical considerations of rock bolting require careful design, extensive geological information, and relatively costly construction. Experience with rock bolting of cavities for reactor siting in Europe, and Norway in particular, indicates that the cost of rock bolting amounts to about 10 to 30% of the total construction cost. The excavation concept proposed here eliminates any need for rock bolting and thus offers numerous constructional advantages.

This concept is within the scope of current technology and offers another unique advantage over construction of a large underground opening in rock: the permeability of the backfill material can be controlled in a reliable manner.

The scarcity of hard-rock sites in the United States is another reason for seeking a different mode of undergrounding. However, even if hard-rock sites were plentiful, the excavation of large volumes of earth or rock is a well-developed technology that can be accomplished at a low cost. For example, a recent excavation bid of $1.75/yd of competent sandstone was recorded at Trinidad, Colorado. The present study used a cost of $2.25/yd of rock and $1.00/yd of soil. Such a narrow cost spread is due to the different but similarly efficient means of removing both materials: explosives for material such as granite, and digging or scraping for weaker soil.

To achieve greater generality, the results are considered as a function of excavation slope (stable profile), depth, and media. The excavated volumes corresponding to Fig. 1 are shown in Fig. 7. The resulting costs, including backfilling operations, are shown in

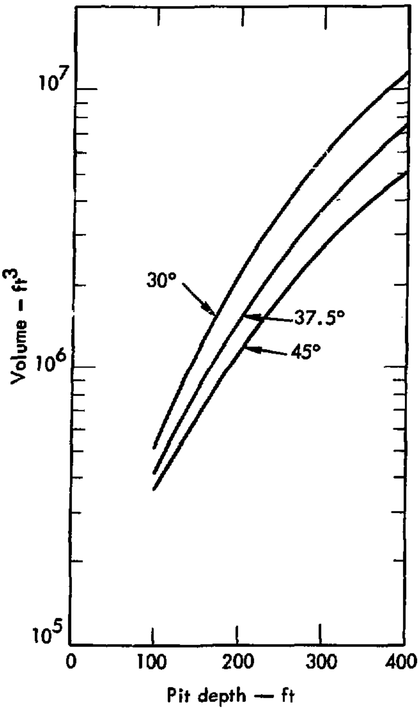

Fig. 7. Volume of conical pit to be excavated. Dependence on excavation slope angle is indicated. (See Fig. 2.)

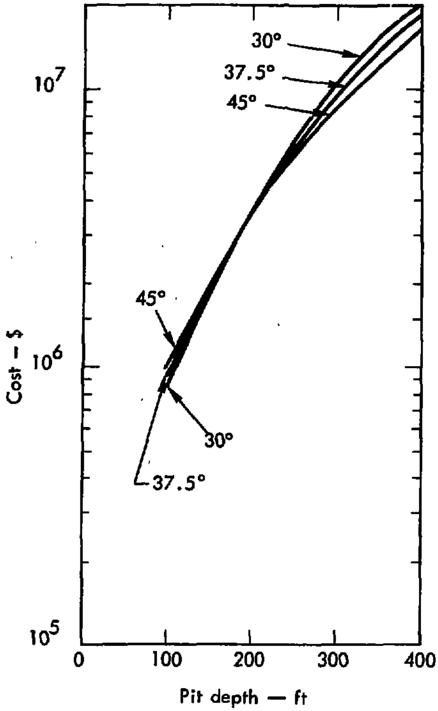

Fig. 8. Excavation and backfill cost for a conical pit and a 130-ft-diam by 135-ft-high shaft at the bottom. Dependence on excavation slope angle is indicated. (See Fig. 2.)

Fig. 8. In developing these data, the excavation for the reactor containment structure foundation is considered to be a volume 130 ft in diam by 135 ft deep with a medium independent excavation cost of $10/yd. Table 4 shows other data. For the dimensions shown in Fig. 2, the total excavation and backfill cost is $4,000,000.

Many sites exist in which the host geologic features are favorable for containment. Use of backfill materials as suggested here will insure effective isolation. Favorable geologic areas include dense or crystalline rocks in the metamorphic and plutonic series and beds of silts, tuff, and clay that contain no aquifers. Semiarid areas with deep natural water table levels also provide favorable siting. For areas having shallow water tables or high water mobility, the specific location would require further investigation; this problem has not been addressed in this study.

Table 4. Excavation and backfill costing data.

Geological medium	Repose angle (deg)	Cost ($/yd³) Remove: Conical pit	Remove: Cylindrical shaft	Replace: Fill
Rock	45	2.25	10.00	1.00
Intermediate	37	1.52	10.00	0.875
Soil	30	1.00	10.00	0.75

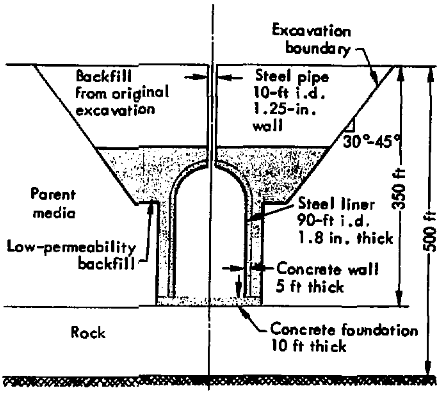

Fig. 9. Reactor containment structure and surrounding media (simplified model for seismic and static analysis). Material properties are given in Table 5.

Table 5. Material properties for the structure shown in Fig. 9.

Material	Young's modulus (ksi)	Poisson's ratio	Density (lb/ft³)
Sand	50	0.40	100
Backfill	100	0.33	120
Parent media	500	0.33	130
Rock	1,000	0.33	160
Concrete	1,000	0.17	150
Steel	30,000	0.33	490

SEISMIC AND OVERBURDEN EFFECTS

The seismic and overburden effects on the containment structure were determined by means of a finite-element method of analysis that included consideration of the effects of the interaction between the soil and the structure.

The first step in the seismic analysis and evaluation of a reactor facility is to postulate possible earthquake ground motions at the site. Once the reactor site has been selected, an investigation of the seismicity and geology of the area permits estimates of both potential earthquake magnitudes and their epicenter locations. With these estimates and knowledge of site soil conditions, one can calculate peak accelerations, amplitudes, and frequency distributions of ground motion for the site.[17]

There are two commonly used approaches to predict the ground accelerations from any given earthquake. One approach uses direct extrapolation of recorded surface motions from past earthquakes to predict the corresponding motions at some epicentral distance. The other estimates the bedrock motion underlying the site and then uses detailed site properties to compute both surface and subsurface motion above the bedrock level. The latter approach was used for this study.

Figure 9 and Table 5 define the containment structure and the extent of the surrounding media. Both the steel liner and the concrete are considered to be integral with a 10-ft-thick foundation located 340 ft below the surface. Extending from the top of the spherical dome to the surface is a 10-ft-diam steel pipe (1.25-in. wall thickness) used for access to the containment structure.

The model extends 500 ft below the surface, where bedrock is assumed. The horizontal boundaries are 500 ft from the axis of symmetry. The model takes into account the various materials shown in Fig. 9. The weight of equipment inside the containment structure is neglected in the analysis.

Since no specific site was considered, the earthquake motions used were arbitrary, as were the properties required to define the media surrounding the containment structure. Both assumptions represent estimates sufficiently realistic for this study.

Two types of loading were considered: an overburden loading and a horizontal earthquake loading applied at the assumed bedrock level. The analyses were separate, but the results can be superimposed.

Figure 10 shows the horizontal component of the acceleration record of the 1971 San Fernando earthquake (Pacoima Dam). This acceleration time history, normalized to 0.2-g maximum acceleration, was used in the analysis. The reactor site was assumed to be sufficiently removed from possible fault rupture that

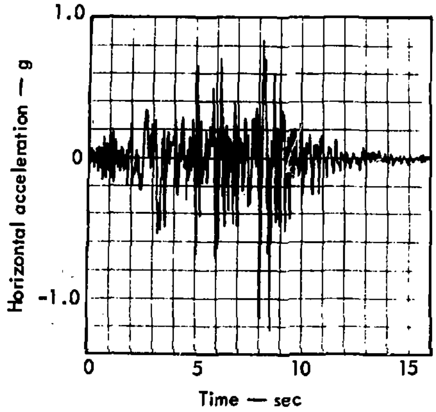

Fig. 10. Pacoima Dam horizontal acceleration record.

local relative ground displacements need not be considered. Because of the granular nature of the backfill material, large local displacements are not likely to form fractures for flow paths for radioactive material.

Figure 11 gives a recently proposed relationship of changes in amplitude and predominant period of rock motion as a function of distance from a causative fault.[18] These relationships are based on a summary of observed and computed rock motion for earthquakes occurring in the western part of North America.

The predominant period of the Pacoima Dam record is ~0.35 to 0.4 sec, which (using Fig. 11) places the reactor site within 25 miles of the causative fault. The 0.2-g maximum acceleration used places the reactor about 2, 10, 18, 25 and 40 miles from causative faults giving rise to earthquakes with magnitudes of 5.2, 5.6, 6.6, 7.6, and 8.5, respectively, by reference to Fig. 12.

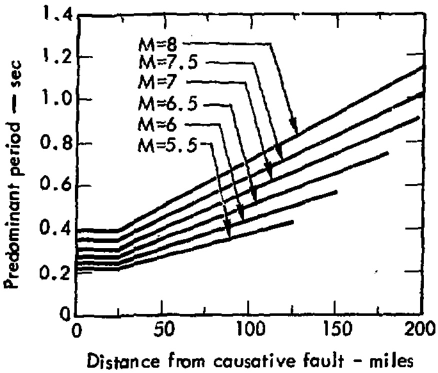

Fig. 11. Predominant periods for maximum accelerations in rock for earthquakes of different magnitudes, M.

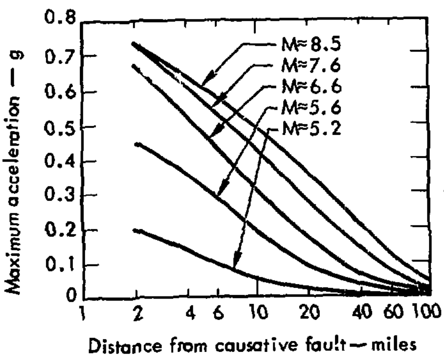

Fig. 12. Average values of maximum accelerations in rock for earthquakes of different magnitudes, M.

All calculations used finite-element programs that treat axisymmetric solids subjected to either axisymmetric or nonaxisymmetric dynamic loads.[19] The results are summarized in Figs. 13 through 15 and Tables 6 through 8.

Figure 13 gives the deformed shape (magnified 500 times) and stress contours of maximum and minimum principal stresses and maximum shear stress from the static overburden analysis. Such information would be helpful when determining excavation cuts and selecting backfill material. By excluding the containment structure, backfill material, and sand, an analysis could be made to evaluate the stability of excavation slopes.

Figure 14 gives plots of maximum axial and hoop stresses in the steel liner and concrete as a function of depth for both static overburden and earthquake loading. The high discontinuity stresses at the pipe/dome interface would be reduced by appropriate detail design. The maximum compressive stresses in the steel and concrete are listed in Tables 6 and 7.

The dynamic earthquake analysis considered the five lowest fundamental modes of vibration. We used 5% critical viscous damping in all modes and materials.

Table 6. Static overburden stresses.

	Axial stress (psi)	Hoop stress (psi)
Steel pipe	-30,000	-5,000
Steel dome	-17,000	-12,000
Steel cylinder	-22,000	-11,000
Concrete dome	-425	-600
Concrete cylinder	-600	-250

Table 7. Earthquake loading stresses in steel components.

	Axial stress (psi)	Hoop stress (psi)
Steel pipe	± 8,000	±15,000
Steel dome	± 7,500	± 8,000
Steel cylinder	± 3,300	± 5,000

Figure 15 shows the first and second mode shapes (magnified considerably), and Table 8 gives the first five natural periods and participation factors of the combined containment structure and surrounding media. As indicated by the 68% participation factor, the combined containment structure and surrounding media respond primarily in the first mode.

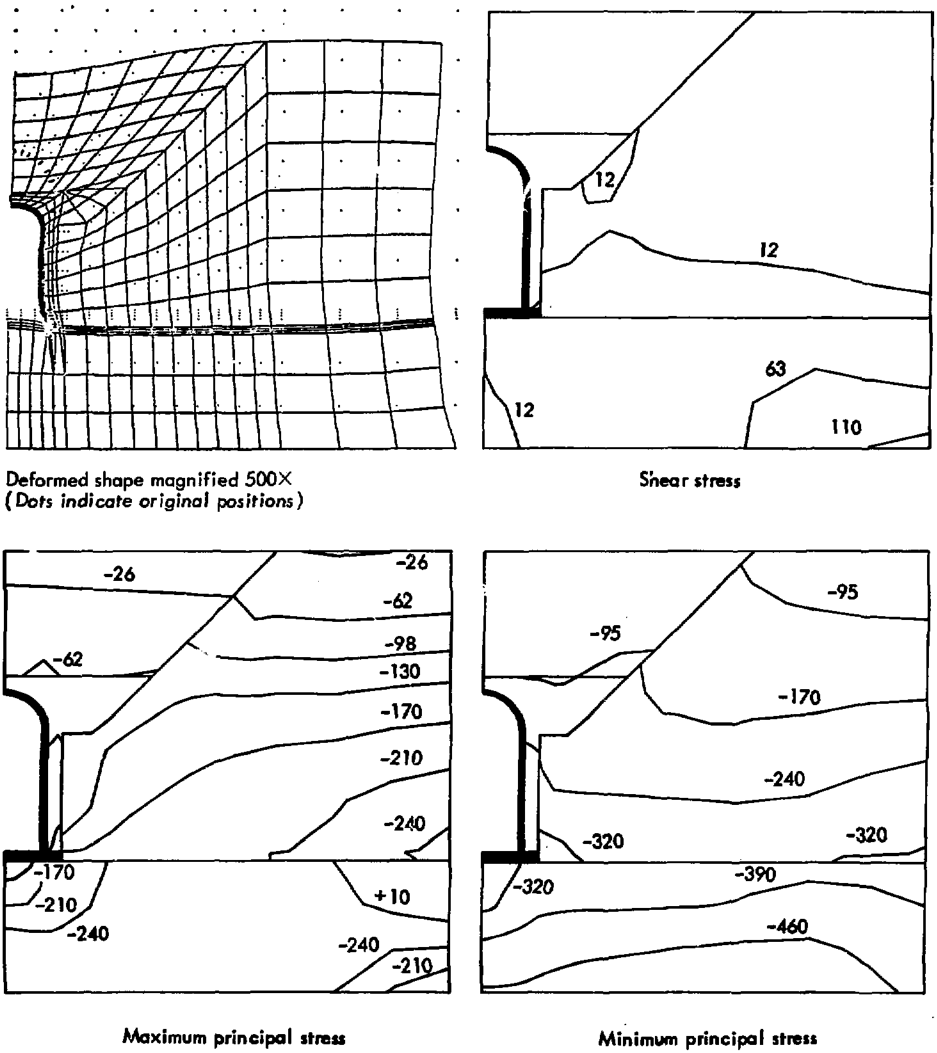

Fig. 13. Results of finite-element calculations for the effect of overburden pressure. Stress values are given in psi.

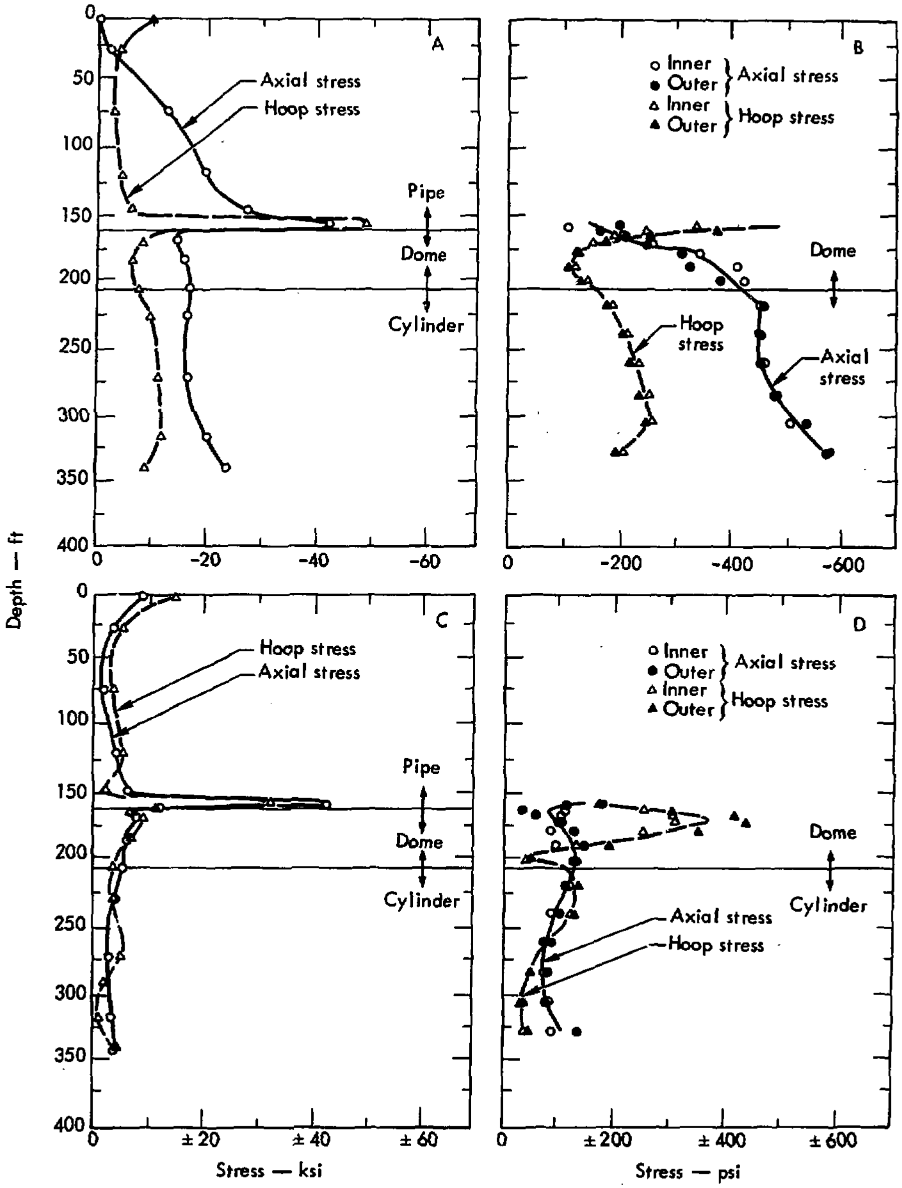

Fig. 14. Stress distribution in steel and concrete in the containment-structure wall. A: Static overburden loading (stresses in steel liner). B: Static overburden loading (concrete stresses). C: Earthquake loading (stresses in steel liner). D: Earthquake loading (concrete stresses).

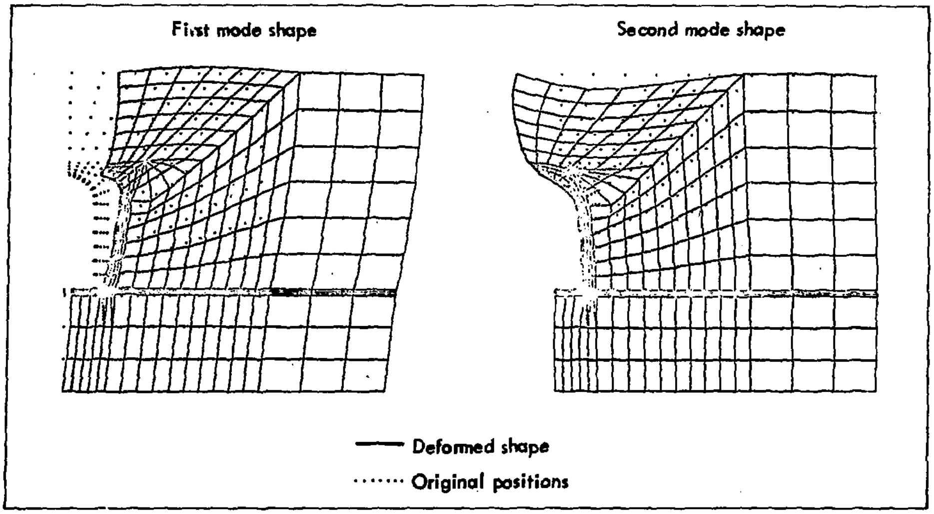

Fig. 15. First and second mode shapes for combined containment structure and surrounding media. Periods and participation factors are given in Table 8.

As expected, the analyses show that the static overburden loading produces stresses that are generally much greater than those produced by the earthquake loading. These calculations also show that more severe earthquake loads can be accommodated.

Table 8. Periods and participation factors.

Mode	Period (sec)	Participation factor (%)
1	0.67	68.0
2	0.40	7.0
3	0.34	7.0
4	0.30	8.0
5	0.26	10.0

PERMEABILITY OF CONTROLLED BACKFILL

Analyses were made to verify containment after a catastrophic reactor accident followed by failure of the containment structure. With failure of the containment structure, radioactive materials would be confined to an envelope within the low-permeability backfill placed around the reactor structure. The backfill permeability is a quantity that can be easily controlled, since the proposed method of excavation permits selection of backfill materials. If rock caverns were used, control of permeability would be difficult.

In accordance with the postulated accident model, a maximum pressure of 70 psia is assumed to exist within the reactor containment structure. If the containment structure ruptures, this pressure is a driving mechanism that forces radioactive solids, liquids, and

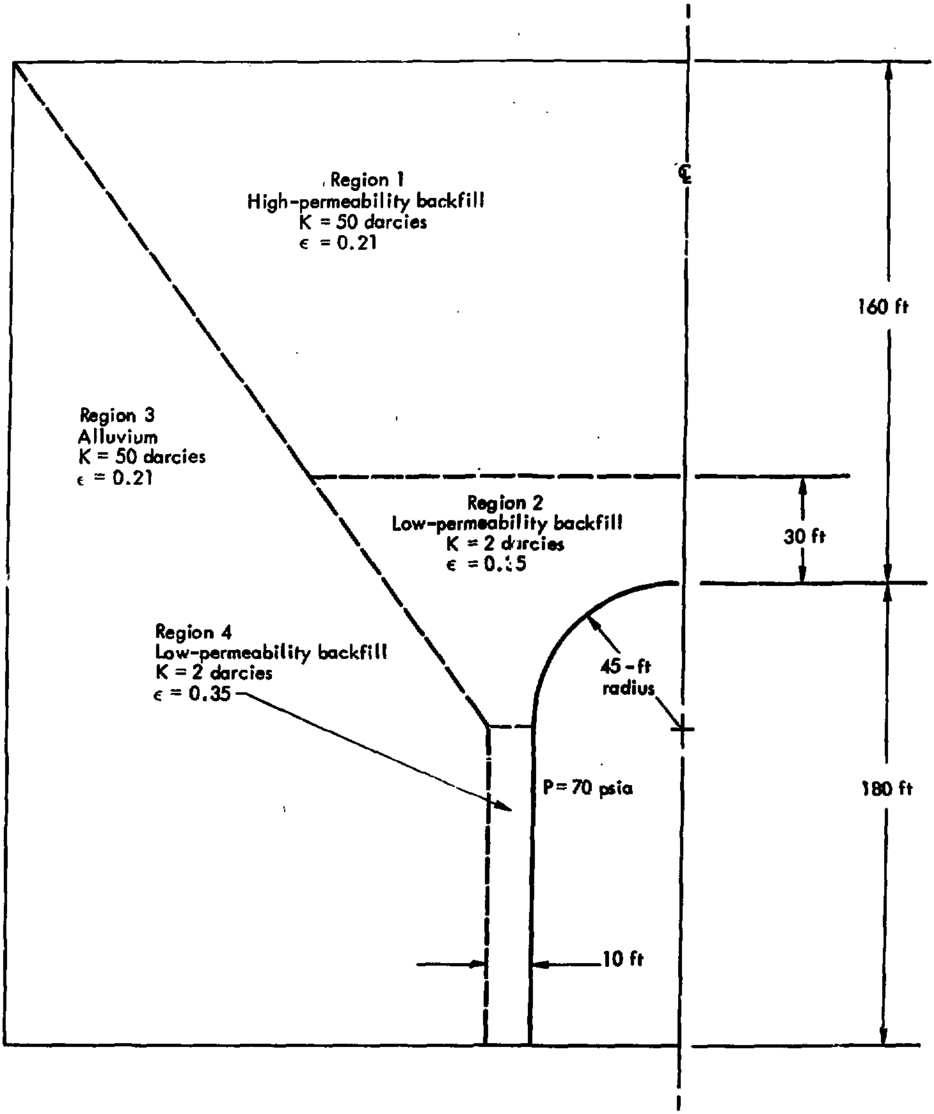

Fig. 16. Zoning for low-permeability backfill design.

gases into the surrounding backfill. Therefore, the method and material of backfill become important in successfully preventing leakage of contaminated gas to the environment.

Calculations were made using an analytical technique developed for determining containment of underground nuclear explosions.[20] The analytical techniques were verified through field and laboratory experiments. Figure 16 shows the configuration of the analysis. The profile shown generates a surface of revolution, representing the reactor containment structure when rotated about the vertical axis.

Confinement capability was calculated for a backfill of alluvium in Region 1 (Fig. 16) having a permeability, K, of 50 darcies and a porosity, ϵ, of 0.25. Included in the backfill was a 10-ft layer of low-permeability backfill (Region 4) outside the cylindrical portion of the containment structure; its permeability was 2 darcies and its porosity 0.35. Region 2, above the containment structure, was backfilled with the same material as Region 4.

In Case 1, the gas was permitted to leak from all points on the vessel wall and dome. In Case 2, leakage was permitted only from the top of the vessel, as if the access riser was sheared off.

In both cases, it was conservatively assumed that the gas in the structure obeyed ideal gas laws. Actually, a condensing fluid would not permeate as far. Also, flow was assumed to be isothermal, so that pressure decay in the structure due to cooling of the structure gas was ignored. The initial pressure in the structure was assumed to be 70 psia. These assumptions modeled the seepage flow through the porous backfill as a

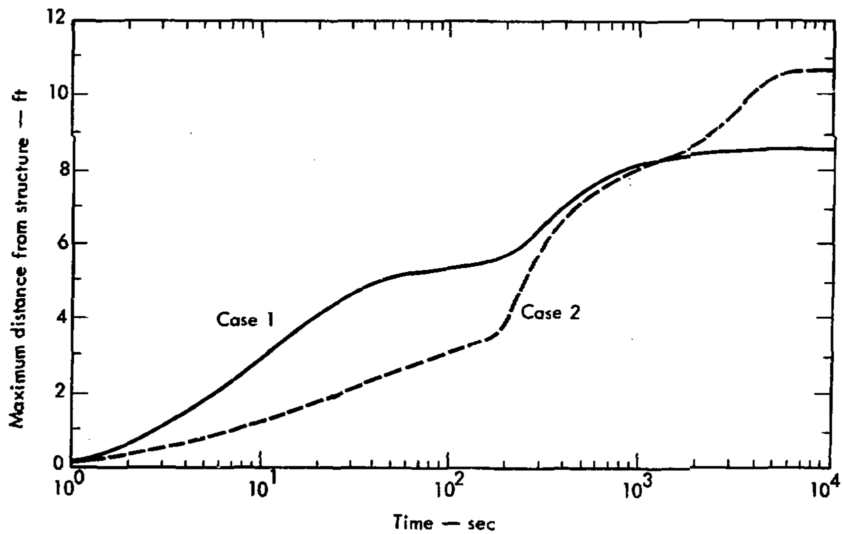

Fig. 17. Radioactive-gas penetration distance.

"worst case." In the actual system, the presence of condensable vapors and the process of structural cooling would reduce the driving pressure available and slow down the interface between the radioactive and the clean gases until the interface would propagate no further. Subsequent motion of the radioactive gas would be possible through diffusion. It is thought that the radiation involved, coupled with the small likelihood of the catastrophic accident, would be acceptable to the public.

The results of calculations made for Case 1 show that the contaminated gas front will propagate into the surrounding media a maximum distance of 8.5 ft from the reactor containment structure. Figure 17 shows a plot of the maximum distance from the structure to the gas front as a function of time. After 44 min, the pressure in the containment structure has decayed to 1 atm, and the gas front can propagate no further. At this time, the gas front is 158 ft below the ground surface.

The consequence of permitting leakage only from the access riser attachment (Case 2) is also shown in Fig. 17. In this case, the gas front moves a maximum of 10.6 ft from the reactor structure to a point 150 ft below the ground surface. After 118 min, sufficient pressure is no longer available to drive the gas front. Figure 18 shows the pressure decay for both Case 1 and Case 2.

These calculations show that the presence of a lower-permeability layer

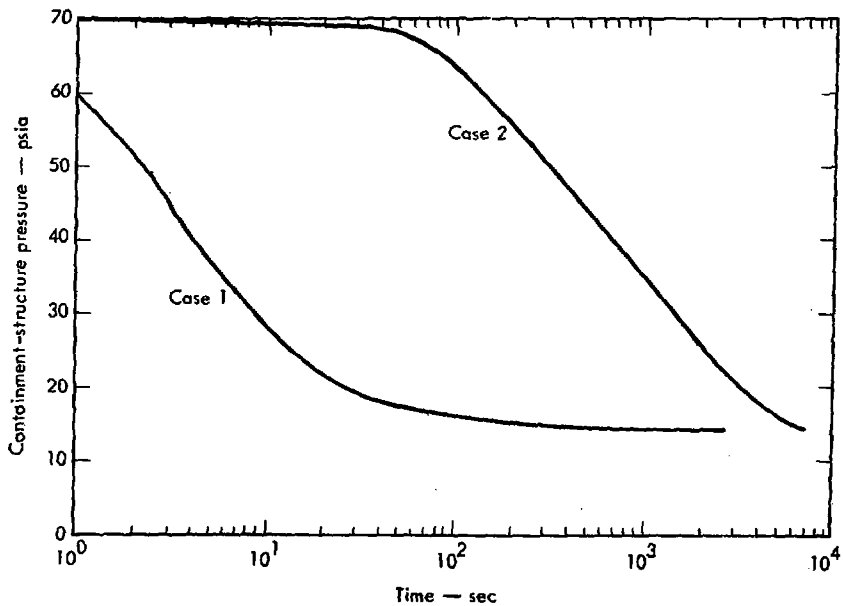

Fig. 18. Internal pressure decay of the containment structure due to flow into porous backfill material.

over the containing vessel prevents leakage to the atmosphere even under "worst case" conditions. The source of pressure and method of backfill prevents the formation of a consolidated material in which hydrofracture is likely to occur.[21] These predictions show that a serious accident does not present a threat of atmospheric or in situ earth contamination resulting from complete failure of the reactor containment structure.

DIFFERENTIAL COST SUMMARY

The comparison of costs is limited to the features affected by undergrounding the reactor. The cost[22] of a conventional 1100-MWe surface plant was assumed to be $400/kWe. Thus its total cost is $440,000,000. Estimated additional costs relative to a conventional surface plant are summarized below.

An evaluation of the maintenance-cost differential indicates that some increase can be expected; this should be considered in subsequent studies. The small cost increase should be offset by the greatly increased flexibility in site selection.

Capital Costs

	Cost differential	
Excavation and backfill	0.9%	$ 4,000,000
Containment structure (assuming wet soil)	0.8%	3,000,000
	1.7%	$ 7,000,000
Other (contingency for "hidden" problems)	1.7%	7,000,000
	< 5%	$14,000,000

Annual Operating Costs

Pumping losses	0.01%	of net electrical output	$ 4,400
Thermal losses	0.04%	of net electrical output	$21,000

Conclusions and Recommendations

The results of this study should be regarded as preliminary in the process of demonstrating underground siting as a viable alternative to present practice in siting nuclear reactor power plants. The first step has been taken by showing that underground siting can be accomplished with existing technology and in a way that is largely independent of reactor type. An important feature of the concept presented here is the Lawrence Livermore Laboratory's highly developed technology in the underground containment of nuclear energy. This technology has been developed from extensive analytical, experimental, and field experience.

We strongly recommend that a more intensive study of our concept be supported as a second step. Such an effort will provide a definitive understanding of the advantages and disadvantages of undergrounding reactors and result in more flexible capability for the siting of future nuclear power plants in the United States. A generalized design was presented to indicate the concept. Detail design considering specific reactor types and sites will lead to further optimization.

The looming energy crisis makes prompt acceptance of this recommendation essential. If our conclusions are supported and the underground reactor becomes a viable alternative, overall plant construction time could be materially reduced by shortening the time from plant proposal to construction permit. This time savings would result from simpler (faster) review for licensing made possible by the increased inherent safety.

As a result of our initial study, we conclude that:

1. By undergrounding large power reactors in suitably backfilled excavations, harmful radiation from the worst possible accident can be confined.
2. Undergrounding in the manner proposed applies to any type of reactor.
3. The additional costs of undergrounding are negligible. In fact, shortened construction times due to reduced environmental-impact effects can be expected, with consequent cost savings.

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